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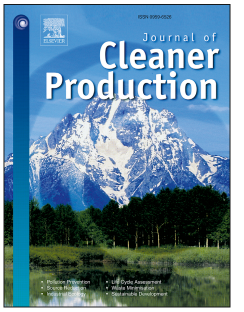

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Plastic waste increases
Pandemic-generated waste
Micro/nano plastics
SARS- CoV-2
Mitigation strategies:
• Public awareness
• Efficient plastic waste management system
• Innovation and scientific research

Prospect of microplastic pollution control under the “New Normal” concept beyond COVID-19 pandemic

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Abstract:

Coronavirus disease (COVID-19) has led to increasing demand for single-use plastic which aggravates the already existing plastic waste problem. Not only does the demand for personal protective equipment (PPE) increase, but also people shift their preference to online shopping and food delivery to comply with administrative policies for COVID-19 pandemic control. The used PPEs, packaging materials, and food containers may not be handled or recycled properly after their disposal. As a result, the mismanaged plastic waste is discharged into the environment and it may pose even greater risks after breaking into smaller fragments, which was regarded as the source of secondary microplastics (MPs, < 5 mm) or nanoplastics (NPs, < 1 μm). The main objective of this manuscript is to provide a review of the studies related to microplastic release due to pandemic-associated plastic waste. This study summarizes the limited work published on the ecotoxicological/toxicological effect of MPs/NPs released from PPE on aquatic organisms, soil organisms, as well as humans. Given the current status of research on MPs from covid-related plastic waste, the immediate research directions needed on this topic were discussed.

Keywords: Microplastics; pandemic waste; single-use plastic; COVID-19.

1. Introduction

The contamination by microplastics (MPs, <5 mm) and nanoplastics (NPs, < 1 µm) has been an issue of concern for years. Despite their occurrences from primary (i.e., direct manufacturing) or secondary (i.e., environmental processes) mechanisms, microplastics and nanoplastics have been found in surface waters, deep ocean trenches, polar regions, high mountains as well as in distant areas (Torres-Agullo et al., 2021). Due to their physical and chemical properties, MPs and NPs have been regarded as an emerging category of contaminants that impose detrimental effects on organisms and the environment. Several studies reported that MP/NP may be released into the environment through wastewater discharges, waste disposal, and so many. They can accumulate in the biological tissues through biomagnification. They demonstrate different toxic levels to organisms at various food chain hierarchies (Khoo et al., 2021; Kwak and An, 2021; Torres-Agullo et al., 2021). The ubiquity of MP and NP poses significant threats to ecological integrity and environmental sustainability.

After the sustainable development goals (SDG) have been proposed by the United Nations (UN), innumerable advocates have shifted the economy-based development strategies to the measures that aim in achieving an ever-lasting sustainable environment. The SDGs of clean water and sanitation, responsible consumption and production, and the life below water are the direct and indirect driving forces that urge more efforts to eliminate land-based contamination of plastic waste which is deemed to be a major source contributing to the prevalence of MPs and NPs. Efficient plastic waste management is the key to tackling the ever-growing plastic pollution. Today, social advancement and economic development are experiencing unprecedented repression due to the COVID-19 pandemic. Single-use items, such as face masks, protection gloves, plastic wraps for food packaging, disposable table utensils, and so many others, have been used extensively to address the issues caused by the prevailing pandemic. These changes owing to the COVID-19 pandemic enhance the occurrence of plastic waste and cause another environmental problem when dealing with the resulting waste in addition to the already existing plastic waste problem.

In light of the above information, the main objective of this manuscript is to answer the following research questions: 1) how has the COVID-19 pandemic elevated the present plastic pollution problem; 2) are there research articles investigating the impact of microplastic generated from the COVID-19 pandemic plastic waste in the environmental matrix; 3) what are the future research directions to tackle the microplastic pollution beyond COVID-19 period. To obtain the answers to the above-mentioned research guiding questions, this manuscript provides an insight into the microplastic-related studies relevant to COVID-19 pandemic-associated plastic waste.

Several papers run a laboratory simulated degradation study on masks to release MPs and characterize them, but the main purpose of this manuscript is to review only those pieces of literature that attempted to study the MPs released from pandemic generated plastic litter in the environment where it is exposed to real-weathering conditions, rather than simulated conditions in the laboratory. Many recent studies have made an exemplary attempt to discuss and/or quantify the amount of plastic waste generated due to the COVID-19 pandemic (Benson et al., 2021; Parashar and Hait, 2021; Peng et al., 2021). To link these limited studies to the impact of COVID-19 generated waste, this manuscript critically reviews the impact of MPs released due to the COVID-19 pandemic on aquatic and soil organisms as well as humans to understand the fate of pandemic-associated plastic wastes. A recently-published review article provides a perspective on face masks and PPE kits being the source of MPs in water bodies, the potential impact of MP on aquatic organisms, and its eventual introduction into the human via food (Ray et al., 2022). In contrast, this manuscript provides a critical evaluation of the impact of MP not only on the aquatic organisms but also on the soil biota, along with the impact of MP inhalation risk to humans due to wearing masks. Wearing masks might be the "New Norm" post COVID-19 pandemic as well. Thus, discussing the impact of MP released due to COVID-19 pandemic generated plastic waste on aquatic organisms, soil organisms, as well as humans mark the novelty of this work. Given the current status of MPs' research on COVID-related plastic waste, the potential research directions were suggested to manage plastic waste beyond the COVID-19 pandemic, including public awareness, the role of government and the plastic waste management system, and the role of researchers and scientists to bridge the scientific knowledge gap.

2. Method for preparing this review

The literature search for this review was conducted by retrieving the research articles using Web of Science and Google Scholar. All articles were searched based on their keywords and title. The keywords used in the search were: microplastic, COVID-19, plastic waste, soil, aquatic, risk assessment, and human. Most relevant articles were screened by abstracts and titles. Firstly, the publication period was constrained to 2020-2022, which represents the COVID-19 pandemic period. Secondly, we screened the articles to analyze only those research articles that conducted the COVID-19 related microplastic studies in the environmental matrix, and not only at the laboratory scale under simulated plastic degradation conditions. Thirdly, the articles were screened and categorized for the presented sections in this manuscript. Additional articles before 2020 were cited to support their applicability to support the information presented in this manuscript.

3. Elevated environmental threat of microplastic due to COVID-19

As of December 15, 2021, 270,791,973 confirmed cases of COVID-19 have been reported globally (WHO, 2021). This number is still increasing since the WHO declared the COVID-19 outbreak on March 11, 2020 (WHO, 2020a). COVID-19 is an infection resulting from the SARS-CoV-2 virus 2 (namely severe acute respiratory syndrome coronavirus 2) that can spread through the minute droplets from a COVID-positive person's mouth and nose when he/she coughs, sneezes speaks, or breathes. Hence, personal protective equipment (PPE) was made essential for frontline workers, patients as well as the population in general (WHO, 2020b). Owing to the outbreak of the COVID-19, the requirement for PPE rose notably, with a requirement of 129 billion face masks and 65 billion gloves monthly to safeguard the general public and frontline workers worldwide (Prata et al., 2020). In addition to PPE utilization, social distancing, travel regulations, and lockdown were employed to curb the spread of COVID-19 (Sun et al., 2020). Individual choices to address safety concerns related to shopping or dining during the ongoing pandemic also increased the generation of plastic waste as people shifted their preference to online shopping and food delivery. It is estimated that 1.6 million tons of plastic waste is generated worldwide per day since the outbreak, and 3.4 billion single-use facemasks or face shields are thrown away daily (Benson et al., 2021). According to the Global Waste Index (2019), 2.0 billion tons of waste are generated per year, 12% of which is plastic (World Bank, 2022), which is equivalent to 0.66 million tons of plastic waste generated daily. Despite the uncertainty in the plastic waste statistical survey, an apparent increase in plastic waste generation during the COVID-19 pandemic is becoming an attention-drawing issue. Fig 1a shows the increase in online shopping and takeaway services during the pandemic for selected countries and the respective amount of total plastic waste generated. For instance, the waste generated as a result of online shopping (in decreasing order) in China, Germany, the USA, India, and Italy during the pandemic was 402,000 tons, 36,500 tons, 2,700 tons, 520 tons, and 450 tons, respectively. The hospital waste generated (in decreasing order) in India, the USA, Germany, Italy, and China was 100,865,0 tons, 685,200 tons, 500,300 tons, 404,00 tons, and 146,00 tons, respectively (Benson et al., 2021; Parashar and Hait, 2021). Fig 1b shows the global contribution to plastic waste, including PPE and hospital waste during the COVID-19 pandemic.

Insert Figure 1 here

The global online food delivery service market increased from $107 billion in 2019 to $111 billion in 2020 with an enhancement of 3.6%. The growth slowed down in 2020 which was suspected due to the economic decline resulting from the COVID-19 outbreak. However, companies started to resume their operations in 2021, and the market grew from $111 billion in 2020 to $127 billion in 2021 at a compound annual growth of 10.3%. The market is expected to increase by 11% and reach $192 billion in 2025 (Businesswire, 2020, 2021). In the course of an eight-week lockdown in Singapore, 1.5 thousand tons of additional plastic waste were generated from packaged takeaway meals and home food delivery (Bengali, 2020). The Environmental Research Institute, Chulalongkorn University (ERIC) reported that the amount of plastic waste increased by 62% between January and April 2020 compared to that of the same period in 2019, and non-recyclable single-use plastic bags, styrofoam boxes, plastic bottles, and cups constituted the majority of the waste. ERIC predicted that the quantity of plastic generated from online food delivery will add up to an average of 4,360 billion pieces per year by 2025 (ERIC, 2021). Increased utilization of single-use plastics during the COVID-19 pandemic aggravated the already-existing problem of plastic waste. In Fig 1a, the takeaway service is used more often in the United States, Vietnam, South Korea, and Singapore, implying more pandemic-related plastic waste generation. The increase in online shopping might enhance the potential for microplastic generation. For China and India, the plastic waste generated is significant due to their massive population. Also, the sudden increase in plastic waste might paralyze the waste disposal and recycling system due to the over-loading of the existing facilities. As a result, the mismanaged plastic waste (MMPW) might be discharged into the environment-streets, rivers, soils, marine coastlines, and oceans, causing an increase in microplastics (Akarsu et al., 2021; Rakib et al., 2021; Okuku et al., 2021).

Although PPE may save lives in the pandemic, the accumulation of plastic waste as a result of discarding and mismanagement of plastic wastes would lead to disruption of the waste management chains, causing serious environmental pollution on land as well as in the aquatic ecosystem. A study conducted in Kenya reported that COVID-19 related waste contributed to approximately 17 % of the combined waste encountered by the side of the urban roads and the coastline comprised mainly of COVID-19 related disposed objects (Okuku et al., 2021). Another study conducted along the coastline of Agadir, Morocco reported a PPE density of 1.13×10^{-5} PPE m^{-2} due to mismanagement of PPE litter (Haddad et al., 2021). Globally, 193 countries generated 8.4 ± 1.4 million tons of pandemic-associated plastic (until August of 2021), as estimated by Peng et al. (2021).

Besides causing severe environmental problems (Hiemstra et al. 2021), plastic litter may become a source of secondary MPs/NPs and pose even greater danger after breaking into smaller fragments (Fadare and Okoffo, 2020; Ma et al., 2021). To be more specific, PPE and takeaway containers are mainly made of plastic polymers, for example, polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), polyethylene (PE), or polyester (Fadare and Okoffo, 2020; Du et al., 2020; Liu et al., 2021: Ma et al., 2021). The different plastic types, their properties, and the items where these plastics are commonly used, apart from masks and PPEs, are given in Table 1. Once the plastics are released into the environment, they slowly degrade due to various factors such as photodegradation, weathering, corrosion, or mechanical forces of water to form MPs and NPs (Aragaw, 2020; Parashar and Hait, 2021). The release of MPs and NPs from the disposable masks has been confirmed in the laboratory experiments. For example, the degradation of masks using mechanical forces of water current was conducted by Morgana et al. (2021) who immersed three-layered surgical face masks (primarily composed of PP) in water and sheared them by a rotating blender (to mimic the aquatic circular waves and motions). The microplastics from the damaged masks were characterized using an optical stereomicroscope (for qualitative analysis) and flow cytometry (for quantitative analysis). This study confirmed the release of MPs and NPs from the disposable-PP masks, and the amount of these weathered plastics increased with the increase in the shear intensity (mimicking the marine flow rate) and exposure time (mimicking the time spent in the environment) (Morgana et al., 2021). Peng et al. (2021) estimated a total discharge of 22 - 30 thousand tons of pandemic-associated plastics to the global oceans, among which approximately 12 thousand tons are microplastics. Not only being present in marine/inland waters, but MPs and NPs find their way into the terrestrial ecosystems as well as in the atmosphere (Wang et al., 2021; Chen et al., 2020; Kwak and An, 2021). Therefore, MPs and NPs may enter the food chains and eventually reach our table through oral digestion, causing the accumulation of toxins, as illustrated in Fig 2. Plastic waste due to household and industrial activities is already high and pandemic-generated waste makes it even higher. These plastic wastes may degrade due to photodegradation and corrosion by ocean waves and microbial degradation (for example). This leads to the formation of microplastics (MP) and nanoplastics (NP). When in soil, MP/NP can impact the soil habitats, including plants and soil microbes and may be transferred through the food chain when the plants or soil worms are consumed by farm animals (for example, cattle and hens). Similarly, in marine habitats, MP/NP can be consumed by fish, and the MP-contaminated plants and meat are consumed by humans eventually.

Insert Table 1 here

Insert Figure 2 here

4. COVID-19 related microplastic studies

Many reports have confirmed the existence of PPE such as disposable masks in Peruvian coastlines (De-la-Torre et al., 2021), South American coastal cities (Ardusso et al., 2021), and Canadian metropolitan areas (Ammendolia et al., 2021). Table 2 summarizes the studies on microplastics released from pandemic-generated plastic waste, including the sampling procedure, microplastic analysis techniques, and the related results. While some studies focused on the possible release of MPs from PPE (for example Robin et al., 2021; Akhbarizadeh et al., 2021), others confirmed their physical release from PPE (for example Loizia et al., 2021; Rahman et al., 2020). As mentioned in Section 3, statistics and data (also depicted in Fig 1) show that the COVID-19 pandemic resulted in an overall increase in plastic waste. However, in some cases, lockdown measures resulted in the reduction of plastic waste due to inhibition of social activities, and henceforth the occurrence of MP was reduced, also. For example, the lockdown in Cyprus decreased the MP concentration from 4.7 % in 2019 to 1.7 % in 2020 at the beach (Loizia et al., 2021). Similarly, the closure of the Seattle Aquarium beach reduced the plastic waste, resulting in an 81% decrease in MP in 2020 (Harris et al., 2021). In contrast, PPE litter increased during the COVID-19 pandemic on the sandy and rocky beaches of Bushehr, Iran (Akhbarizadeh et al., 2021), and Cox’s Bazaar, Bangladesh (Rahman et al., 2020). During the lockdown, while the use of PPE, masks, and single-use plastics increased because of the pandemic, the plastic waste management system in these countries collapsed. Therefore, PPE and plastic litter ended up on the coastal shorelines. An enhancement in MPs/NPs occurrence should be expected due to increasing plastic waste. A proper waste management plan should be in place to control the plastic waste generated during the pandemic. In an air sample monitoring study conducted near a hospital complex in Sao Paulo, Brazil, MPs were found in the forms of airborne particles ranging from nil to 0.9 unit·m^{-3} as well as fibers in the range of 9 -24 unit·m^{-3}. The presence of these MP in the air can be a potential carrier of the virus, including SARS-CoV-2 aerosols, facilitating virus entry into the human body (Amato-Lourenço et al., 2022). Hence, the fate of MPs released from pandemic-related plastic waste should be investigated not only in the terrestrial or marine environment but also in the atmosphere.

While microscopy (e.g., scanning electron microscopy (SEM), optical microscope, or fluorescence microscope) and FTIR (Fourier transform infrared spectroscopy) are the two most common techniques to determine the chemical composition of the polymers comprising MPs (see Table 2 for details), carbonyl index also throws insight on the polypropylene-polyethylene photooxidation of PPE, thus indicating how long the PPE was exposed to the ambient environmental conditions. Carbonyl index is defined as,

$$\text{Carbonyl index (CI)} = \frac{A_1}{A_2} \qquad \text{eq 1}$$

where A_1 is the absorbance at 1715-1735 cm^{-1}, the reference peak for the carbonyl group, and A_2 is the absorbance at 1471/1460 cm^{-1}, reference peaks of polyethylene/polypropylene, respectively (Rodrigues et al., 2018). The study by Akarsu et al. (2021) showed that the carbonyl index of face masks collected from Mersin, Adana, and Niğde in Turkey ranged from 0.11 to 0.33, which represents that the oxidation values of PE were low, and 3 out of 4 samples were found to be slightly oxidized, implying that the masks spent more time in the environment.

The studies summarized in Table 2 were in the preliminary stage and intensive environmental impact assessment is required to understand the effect of MPs under ambient conditions. The plastic litter caused by PPE and face masks were found around the world. The release of MPs/NPs from PPE was evaluated under laboratory conditions and the release of MPs was simulated.

Insert Table 2 here

5. Effect of microplastics on aquatic organisms, soil organisms, and human health during COVID-19 pandemic

The COVID-19 pandemic-generated plastic waste was disposed of into the environment and became a significant source of MPs and NPs in the aquatic system as well as the soil environment. Once released, the MPs and NPs might pose a health risk to living organisms. Table 3 summarizes a few studies that are available regarding the effect of MPs/NPs released from PPE on aquatic organisms, soil organisms, and humans. The study by Ma et al. (2021) showed that masks release a large quantity of MPs and NPs that can remain in the environment or be inhaled by the mask wearers. The ingestions of MPs and NPs released from the mask by marine organisms, including marine diatom (*Phaeodactylum tricornutum*), rotifers, copepods, shrimp, scallops, and groupers, were examined. Even a brief period of exposure lead to the adsorption of the mask weathered components onto the diatom's body, thus hindering their photosynthesizing capability. Additionally, these weathered mask components could be assimilated by the marine organisms, as evidenced by the analysis of the digestive tracts of various organisms (including rotifers, copepods, shrimp, scallops, and groupers) that confirmed the presence of MPs/NPs. Ma et al. (2021) evaluated the retention of MPs in human nasal mucus and found that the nasal cavity of a person contained 6.6 ± 4.9 MPs per mg of nasal secretions after wearing the face mask for a brief period of time. It can be speculated that the MPs/NPs in a human body should increase because of enhanced ambient MPs/NPs due to the COVID-19 pandemic. Even in the post-COVID era, MPs/NPs may remain relatively high in concentration since they are quite stable if no effective way to reduce environmental MPs/NPs was proposed.

Sun et al. (2021) evaluated the chronic toxicity of the MPs released from surgical masks, dominated by sizes of <10 μm, to the marine copepod (*Tigriopus japonicus*), which plays an important role to link primary producers with higher marine consuming organisms, where copepod is the primary source of food for the higher marine consumers, thus an important organism of the food chains. Sun et al.'s (2021) result demonstrated that the copepods ingested the MPs, causing a significant decline in their fecundity. The reduced fecundity would lead to depletion in food reserves for copepod higher consumers and eventually lead to aquatic ecosystem imbalance. Ingested MPs, as well as their distribution along with their guts and body, were confirmed through fluorescence imaging. Using copepods as a model, this study was able to demonstrate that MPs accumulate in copepods and establish that they have the potential to accumulate in higher marine organisms through bioaccumulation and biomagnification.

A biomonitoring study was conducted in Songkhla Lake, Thailand, during COVID-19 by Pradit et al. (2021) who reported the presence of MPs (particularly PE and polyester fibers) in the stomachs/gut of catfish (*Arius maculatus*), spear shrimp (*Parapenaeopsis hardwickii*), and yellow shrimp (*Metapenaeus brevicornis*), and these three species are the ones commonly consumed by people around this Lake. Approximately 170 MP pieces were found in the gut of the marine organisms (n =47) under test (details are given in Table 3). The amounts of MP debris accumulated in the guts of fish and shrimp were approximately 3 times greater than that during the pre-COVID-19 pandemic (Azad et al., 2018).

MPs are not only a major emerging contaminant for marine organisms, but also pose threats to agricultural production because they can adsorb certain chemical pollutants such as hydrophobic organic chemicals (HOCs) (Hartmann et al., 2017), antibiotics (Li et al., 2018), and heavy metals (Öz et al., 2019), and mediate its translocation in the terrestrial environment. Kwak and An (2021) attempted to understand the ecotoxicological effects of face mask filters (MB fillers) that have been discarded due to the COVID-19 pandemic on the soil species of earthworm and springtail (as an example of soil invertebrates). The soil bioassays results showed that MB filter fibers and their fragments were found to hinder reproduction and growth in springtails, and suppress earthworm spermatogenesis, suggesting that they could negatively impact the next generation of soil species pool and disrupt the soil ecosystem.

In addition to the environmental implications of discarded masks, evaluation of their human health consequences would be of interest as well. Wearing face masks has become the "new normal" daily practice due to COVID-19. There has rarely been a report of MPs inhaling due to wearing masks. Surgical masks are made up of three layers, the front and rear layers comprises of PP (fiber diameter ~ 20 μm), and a middle layer (core material for virus rejection) made of melt-blown fabric (polypropylene (PP) as the major component) (Pu et al., 2018). MPs or NPs can be generated during the use/reuse of masks and may lead to the risk of MP/NP inhalation via the route of breathing (Aragaw, 2020, Fadare and Okoffo, 2020). According to several studies, prolonged inhalation of fibrous particles may cause cancer (Prata et al., 2018; Siegel et al., 2020). Meanwhile, Torres-Agullo et al. (2021) discussed the implications of using face masks during the COVID-19 pandemic and emphasized the need for further research on the mechanism of translocation of MP to the blood, and the consequent lung deterioration mechanism (Amato-Lourenco et al., 2020; Torres-Agullo et al., 2021).

Insert Table 3 here

6. Plastic waste management beyond COVID-19 pandemic

Based on the summaries of the above studies, it appears that MPs/NPs must be minimized through better environmental management, policies, and laws ensuring proper disposal of single-use plastics generated during the COVID-19 pandemic. To combat the COVID-19 pandemic, countermeasures, such as the social distancing, work-from-home (WFH) mechanism, and real-name registration for in-shop purchases, have been enforced. At the same time, wearing a face mask and the use of PPE remain suggested during outdoor activities or meeting physically with others. Corporate employees are given the choice if they prefer to work remotely. Before the COVID-19 pandemic, plastic waste management strategies were in place. However, the COVID-19 pandemic shifted the practice of re-using appliances to single-use utensils due to pandemic control, which further increased our dependence on plastic. To manage plastic waste beyond the COVID-19 pandemic, perspectives on the challenges and future research directions are discussed and categorized into three subsections: 1) public awareness; 2) role of government and plastic waste management system; and 3) role of researchers and scientists to bridge the scientific knowledge gap.

Firstly, awareness of microplastic generation as a result of pandemic-related waste and single-use plastic needs to be established. Recent studies on MP pollution showed that there was limited awareness regarding plastic PPE that could be a source of environmental MPs. Because of the lack of such awareness, PPE might be discarded without being handled properly. Strategies to address social awareness can include public education regarding the threat of microplastic release from single-use plastic, and how overconsumption of such plastic would eventually lead to deterioration of the environmental ecosystem and human health in the long run. This could be achieved by promoting environmental education and inculcating the values of the solution for plastic contamination to the next generation (Ries et al., 2016). Efforts have been made in various cities, under the initiative “Plastic smart cities by World Wide Fund (WWF) for Nature, to hold public awareness programs and campaigns to spread the knowledge on the plastic pollution threat and mitigation actions that can be taken to tackle the problem, thus providing a tool to become a part of the initiative and be actively engaged to create a plastic smart city (Plastic Smart Cities, 2022). For example, a French NGO named “No Plastic In My Sea” facilitates a public event every year to reduce the consumption of single-use plastics and promotes such event on a social media using the hashtag “#NoPlasticChallenge to reach out to the millennials, youngsters, and people active on social platforms (Plastic Smart Cities, 2022). With adequate awareness activities, one can bring about a change in people’s choice of living by influencing their mindset towards mindful shopping decisions and proper sorting and recycling of their plastic wastes. Proper sorting of beyond-COVID-19-generated plastic waste including masks and PPEs will make it easier for the community waste management system to further handle the plastic waste and reduce the possibility of the litter reaching marine shorelines or terrestrial dumping grounds. In terms of online shopping and take-out food services, buyers, as well as service providers (e.g., stores, and restaurants) should opt for recyclable packaging or containers.

Secondly, there is an urgent need to establish an effective plastic waste management system beyond the COVID-19 pandemic so that plastic disposal does not pose environmental threats. Introduction of labeling and providing proper information on the type of plastic on the masks, PPE, take-out containers, online order packaging, and all types of plastic would make it easier to identify the MP/NP expected to be released from the source plastic. A few decades ago, there was no differentiation between recyclable waste and non-recyclable waste, but nowadays we have a sorting system in place for these two types of waste. Similarly, providing additional information on the types of plastic used for manufacturing would help further strengthen the waste sorting system. In the coming 5-10 years span of time, these data would help to understand the predominant plastics and assist researchers and scientists to focus on explicit research directions to mitigate the environmental impacts of specific plastics (e.g., PP, PS, etc.). Enforcement actions from the government side will be needed to mitigate plastic pollution. Certain countries do have related plastic waste mitigation plans implemented. For example, Brussels (Europe) follows a “Zero Waste Strategy” where online resources are available to help the community to sort the waste and to promote zero waste strategies (Plastic Smart Cities, 2022). Another example is in Greece, where the “Waste Prevention Education” program developed a guidebook for students and teachers to be included in the school curriculum with the aid of the regional municipality leaders

(Plastic Smart Cities, 2022). These examples align with the previously mentioned strategy of spreading public awareness; however, implementation from the government side is required, implying the integrated roles of the government and the non-governmental organizations (NGO, for example, WWF for Nature) to bring about the change. Government and policymakers can draw inspiration from these stories and try implementing them in their countries.

Lastly, ongoing research to mitigate the MP threat as a result of plastic pollution should focus on pandemic-generated wastes, taking into consideration the recommendation discussed herein. While studies of the MP risk to marine organisms have been conducted, the focus may be expanded to the examination of risk to soil biota. MPs from PPE and food containers for the aquatic system are an emerging contaminant of concern, and research should be conducted on the environmental risk assessment, fate, source, and biological effects, as well as human impact assessment. MPs/NPs from ambient plastic waste can be ingested by higher marine organisms and microorganisms in the aquatic system, resulting in chronic health problems for humans by entering food chains. Future research should include long-term monitoring experiments to assess the ecotoxicological impact on different biota. The fate and transport of MPs and NPs should be investigated. Connecting back to the previous suggestion on MP labeling of the plastic to assist in the sorting system in the future, scientific research can focus on technical treatment to biodegrade the MPs. For example, biotechnology employing microbial strains has been suggested by Allouzi et al. (2021) as a potential tool to biodegrade MP/NPs. *Aspergillus clavatus* has been shown to biodegrade LDPE (Mor and Sivan, 2008), *Rhodococcus ruber* could biodegrade PS (Gajendiran et al., 2016), and *Bacillus subtilis* has been demonstrated to biodegrade PET (Huang et al., 2018). Even some algae have been shown to produce secondary metabolites that can biodegrade microplastics, for example, *Phormidium lucidum* and *Oscillatoria subbrevis* can biodegrade PE and LDPE (Chia et al., 2020). Further research should focus on the optimal conditions (for example, temperature, pH, and carbon sources) for the biodegradation of MP/NP using biotechnology (Allouzi et al., 2021).

Efforts should be expended to provide eco-friendly PPE and food containers as a replacement for plastic-made items. Possible solutions include the consideration of biodegradable plastics such as polyhydroxyalkanoates (PHA) and poly(lactic) acid (PLA) that can be derived from microorganisms and microalgae (Anderson and Shenkar 2021; Silva et al., 2021; Chia et al.,

2020) or natural fibers rich in polysaccharides, lipids and proteins (Luhar et al., 2020; Das et al., 2020; Yan et al., 2016). The main challenge would be integrating these eco-friendly materials into the already existing infrastructure where synthetic polymers are employed to manufacture the masks, PPEs, and other plastic-related products (that gained demand during the pandemic, including take-out containers). Additionally, innovation and research would be needed to bring down the cost of manufacturing since biopolymers are more expensive than synthetic polymers (Pandit et al., 2021). Further research needs to focus on manufacturing bio-based sustainable masks having the same standards, in terms of antiviral/antibacterial property, and integral strength, as compared to the currently available synthetic masks. Cellulose is an ideal candidate to be used as an alternative for synthetic polymers because it is biodegradable, renewable, less costly, and widely available. But, it can lose its integrity when it comes in contact with water because of its hydrophilic nature (Garcia et al., 2021). Therefore, it needs to be blended with other materials to combat this challenge. For example, gluten, from wheat cereals, showed to possess viral filtration efficiency, and when blended along with polyvinyl alcohol (PVA), the biomaterial also exhibited excellent mechanical strength, equivalent to the standard of the synthetic masks (Das et al., 2020).

Based on the summary of the COVID-19 related microplastic studies, we observed that there is a lack of research articles that investigated the impact of microplastic released from online shopping packaging and takeaway food containers. There are a couple of available studies that investigated the release of MP from takeaway food containers at a laboratory scale under artificial weathering/degradation conditions to characterize the types of microplastic released from these food containers (Du et al., 2020; Fadare et al., 2020). Future studies should focus on monitoring experimental sites to collect these online shopping packaging and takeaway food container litters and investigate their impact on the environment. During waste sorting, the litter would be either recycled, incinerated, or will deposit in a landfill (Evode et al., 2021). The immediate concern should be if the existing plastic waste management system is efficient enough to handle such increasing plastic waste.

While masks might lead to a small amount of MP and NP inhalation, they are crucial during the COVID-19 pandemic. The wearing of masks by frontline workers may increase their risk of exposure to NPs (Han and He, 2021). Humans have been exposed to MPs for a long time and there is little concrete scientific evidence on “no risk” due to MP exposure. It also implies that continuous exposure of NPs and MPs could potentially affect human health, given the direct exposure route due to wearing masks daily during the pandemic. Exposures of MPs/NPs to humans and their toxicity is not well reported so far. Thus, it is difficult to conclude the risk of humans due to MP/NP exposure. Also, the need for human studies to gain insight into the effect of MP/NP is apparent. Leslie and Depledge (2020) questioned if human exposure to microplastics is safe. Therefore, research is needed to understand how the MPs/NPs released from the PPE may affect human health both in short- and long-term inhalation by wearing masks.

7. Conclusion

COVID-19 poses serious health risks and as a combat measure, the use of PPE, online shopping, and food delivery seems inevitable, which might result in more plastic waste generation. With this study, the investigations related to MP threat due to COVID-19 generated plastic waste were summarized. Microplastic and nanoplastics have harmful effects on the aquatic system as well as soil biota. These small particles can be readily assimilated by aquatic organisms, such as fish, or taken up by plants from the soil as bioavailable nutrients. They are eventually consumed by humans and microplastic enters the food chain. Therefore, future research should focus on human health and ecosystem stability during and after COVID-19 pandemic. As we see from our discussion on the challenges and future research directions recommended in this manuscript, it is necessary for all stakeholders including government, policymakers, waste managers, and researchers to collaborate to solve the problems of mismanaged plastic waste. Waste management and mandatory regulations, as well as environmental awareness, are the most important components of eliminating single-use plastic waste. Government, researchers, public community, and industries need to collaborate to tackle the issue of plastic pollution. The public needs to recognize its responsibility toward waste disposal and sorting, purchase decisions, and choices (whether to go plastic-free or consider prioritizing recyclable products). Industries need to rethink and redesign their supply chain to include sustainable alternatives. The government needs to incentivize and encourage such practices and initiatives to achieve an efficient plastic waste management system. When all these sectors are linked and work towards a common goal of plastic pollution mitigation, what will be achieved is a sustainable plastic circular economy (Yuan et al., 2021).

CRediT authorship contribution statement

Fatima Haque: Formal analysis, Investigation, Writing- Original Draft, Review, and Editing. **Chihhao Fan**: Conceptualization, Writing- Supervision, Review, and Editing.

Conflicts of interest

There are no conflicts to declare.

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Table 1: Properties and common single-use of different types of plastic found in the environment (US EPA, 1992; Nuelle et al., 2014; British Plastics Federation, 2017; Alabi et al., 2019).

Plastic-type	Abbreviation	Properties	Single-use plastic items	Other common uses
Polystyrene	PS	Density (1.04-1.08 g/cm^3) transparent, hard.	Takeaway containers, packaging material, polystyrene cups (foam cups), and disposable plastic cutlery.	Toys, video cases, fake glassware.
Low-density polyethylene	LDPE	Density (0.89-0.94 g/cm^3), translucent, soft.	Clingy plastic wraps and films, bread bags, and paper towels.	Irrigation tubes, mulch coatings, plastic squeeze bottles.
High-density polyethylene	HDPE	Density (0.94-0.97 g/cm^3), opaque, hard/semi-flexible.	Cereal box liners, freezer bags, and grocery bags.	Shampoo bottles, milk jugs, pots, household cleaning products, crates.
Polypropylene	PP	Density (0.89-0.91 g/cm^3), translucent, hard.	Straws, packaging tapes, snack bags (chips and biscuit bags), ice cream tubs, juice packs/bottles, and disposable cups	Microwave-safe containers, lunch boxes, and clothes hangers.
Polyvinyl chloride	PVC	Density (1.3-1.58 g/cm^3), transparent (clear), hard.	Blood bags, single-use medical supplies.	Cleaning products, pool liners, automobile products.
Polyethylene terephthalate	PET	Density (1.29-1.4 g/cm^3), transparent, hard.	Clamshell packaging in takeaway containers such as salad domes, biscuits and snack trays, and bottle caps.	Water and soda bottles, jugs, jars.
Others	Ex.:polyester, polyamide (nylon)	Density of polyester (1.01-1.46 g/cm^3), Density of polyamide (1.13-1.35 g/cm^3).	Packaging, nylon products.	Appliance parts, electronic parts, safety glasses.

Table 2: Summarized results of microplastic studies conducted during the COVID-19 pandemic

Location	Sample source	Sampling procedure	Analysis	Result summary	Reference
Bushehr, Persian Gulf coast (Population: 223, 504).	Sandy and rocky beaches. Plastic source includes discarded PPE.	Discarded PPE samples were procured from 9 zones sampled 4 times over 40 days.	Following air drying at room temperature, the PPE sampled were analyzed using a microscope to check for MP.	For the sample collected each day, >10% of the sampled PPE has deteriorated. This increases the risk of MP introduction into the coastal waters.	Akhbarizadeh et al., 2021
Chennai, India (Population: 10 million)	A representative number of PPE samples were collected from around the coastal city.	Commercially bought PPE samples were used.	PPE samples were artificially damaged by cutting them into smaller pieces, before analysis using FTIR-ATR	FTIR confirmed the presence of the following polymers in the PPE: polypropylene (25.4%) and polyester (15.4%).	Robin et al., 2021
Cyprus (Population: 40,000-75,000)	Beach. From 2019 to 2020, the sand samples were collected. Plastic source includes items from tourism activities: food packaging waste, straws, cups, bottles, textile waste, and electronic equipment waste.	Sand samples were collected from the high-water mark zone (n = 10), middle of the beach (n = 15), and the pedestrian fronts (n = 10).	1: 2.5 (g/ml) of sand sample and hypersaline solution (10% v/v NaCl) was allowed to stand for 7 min to separate the MP. The collected MP was air-dried before passing through different sized sieves to classify the samples as macro- (2.5–50 cm), meso- (0.5–2.5 cm), and micro plastic (< 0.5 cm).	From 4.7% in 2019, the MP concentration decreased to 1.7% in 2020, owing to lockdown measures.	Loizia et al., 2021
Sao Paulo, Brazil (Population: 11.8 million)	Outdoor air samples were collected. Plastic source includes airborne suspended particles coming from a	For 1 day, the total suspended particles (TSP) samples were collected with the help of an air sampler. To ensure the sampling was performed at an appropriate height equivalent to an adult's	MPs in the air samples were analyzed under a fluorescence microscope, followed by FTIR-ATR.	The observed MP predominantly consisted of polyester (80%).	Amato-Lourenço et al., 2022

	medical center generating hospital and biomedical wastes.	average breathing height, the sampling height was maintained at 125 cm.			
Cox's Bazar, Bangladesh (2 million tourists)	Sandy Beach. Plastic source includes fishing activities (example, gillnet) and tourism activities (single-use plastics, food packaging).	21 zones were sampled for sediments. Sampling was carried out for each 0.25 m^2 area, collecting 1 kg sediment for each area.	Density separation using aqueous zinc chloride was carried out to separate MP. Secondly, the wet peroxide oxidation process was used to separate the biotic materials present in the sediment samples. The final MP extract was analyzed under a microscope followed by FTIR.	MP concentration in the range of 5.2-11MP kg^{-1} was reported, predominantly comprising of PP (47%) and PE (23%).	Rahman et al., 2020
Seattle, Washington, USA.	Seawater (SW) from Seattle aquarium. Plastic source includes effluent discharge from nearby urban households and industries, and tourism activities.	January – July 2019: every month water samples were collected. August 2019-2020: biweekly water sampling performed. After water sample collection, it was passed through a sieve to trap the MP.	The oil extraction method was used to separate the MP from biotic material, followed by visualization under a microscope and micro-Fourier Transform Infrared (μFTIR) spectroscopy analysis.	For each liter of the water sampled in 2019, 0-0.64 MP pieces were found, predominantly composed of fibers. In 2020, MP concentration decreased by 81%, owing to lockdown measures.	Harris et al., 2021
Mersin, Adana, and Niğde, Turkey (Population: 4 million)	Masks found within these coastal cities were collected. Plastic source includes the littered face masks.	Geographical information system (GIS) was used to determine the area before collecting the discarded masks from these three cities.	Collected masks were sterilized using ethanol prior to analysis using FTIR and SEM.	Mask composition included 83.3% PP, and 16.7% PE. A carbonyl index of 0.11 to 0.33 was reported, representing lower oxidation values of PE. 75% of the samples showed slight oxidation which means they spent a long time exposed to the ambient conditions.	Akarsu et al., 2021

Hong Kong	Beach. Plastic source includes surgical face masks.	Disposed surgical masks (SM) were procured from a local beach.	SMs were washed in MilliQ water, prior to soaking in artificial seawater to release the MP from the SM into the seawater, followed by shaking for 9 days at 200 rpm at 25°C. The MP enriched samples were collected and vacuum filtered before analysis using a microscope and FTIR.	The MPs released from SMs were mainly composed of fibers and fragments, predominantly of sizes <10 µm, equivalent to 33% of the total MP. The deterioration rate of fragment MP (176-244 fragments day^{-1}) was greater than that of fiber MPs (~60-100 fibers day^{-1}). Functional peaks for PP were observed in the FTIR spectrum.	Sun et al., 2021

Table 3: Impacts of microplastics and nanoplastics generated during COVID-19 pandemic on aquatic and soil organisms as well as on human health.

Target organism	Plastic Type	Size	Impact	Reference
Marine diatom *(Phaeodactylum tricornutum)*	PP	5 nm - 600 µm, < 1µm[a]	Affect their ability to perform photosynthesis.	Ma et al., 2021
Rotifers *(Brachionus rotundiformis)* Copepods *(Parvocalanus crassirostris)* Shrimp *(Penaeus vannamei)* Scallops *(Chylamys nobilis)* Juvenile grouper *(Epinephelus lanceolatus)*	PP	5 nm - 600 µm, < 1µm[a]	MPs/NPs were found in the digestive tracts of these marine organisms. MPs/NPs accumulated in the marine organisms can enter the food chain as seafood and eventually reach humans.	Ma et al., 2021
Marine Copepod *(Tigriopus japonicus)*	PP	<10 µm[a]	Significant decline in their fecundity. MP ingestion.	Sun et al., 2021
Catfish *(Arius maculatus)*	Rayon, polyester, polyvinyl alcohol, PE, paint	30% of 0.5-1.0 mm size and 1.5-5.0 mm size, 26.7% of 0.15-0.5 mm size, and 13.3% of 1.0-1.5 mm size[b]	Occurrence of 2.73 MP pieces in the stomach (90% fiber, 10% fragment).	Pradit et al., 2021
Spear shrimp (*Parapenaeopsis hardwickii*)	Rayon, polyester, polyvinyl alcohol, PE, paint	33.8% of 0.5-1.0 mm size, 25.7% of 0.15-0.5 mm size, and 16.2% of 1.0-1.5 mm size[b]	Occurrence of 4.11 MP pieces in the stomach (100% fiber).	Pradit et al., 2021
Yellow shrimp (*Metapenaeus brevicornis*)	Rayon, polyester, polyvinyl alcohol, PE, paint	44.1% of 0.5-1.0 mm size, 19.1% of 0.15-0.5 mm size and 1-1.5 mm size, and 17.6% of 1.5-5.0 mm size[b]	Occurrence of 3.78 MP pieces in the stomach (100% fiber).	Pradit et al., 2021
Springtails *(Folsomia candida)*	PP	<300 µm[a]	Reproduction and growth of juvenile organisms were repressed.	Kwak and An, 2021

Adult earthworms *(Eisenia andrei)*	PP	<300 µm[a]	Mask fibers and fragments resulted in spermatogenesis suppression.	Kwak and An, 2021
Human, nasal mucus	PP	5 nm - 600 µm, < 1µm[a]	6.6 ± 4.9 MPs were found in each of nasal secretions as a result of wearing masks.	Ma et al., 2021
Human	PP, PE, PA, PEC, PET, PMMA, PU, PVC	20 - 500 µm, with 20-30 µm (46%) 30–100 µm (45%), and 100–500 µm (9%)[b]	Microplastics were observed during the breathing simulation experiment with masks. Inhalation risks.	Li et al., 2021

[a] size of MP exposure
[b] size of MP found inside the organism or inhalation tests

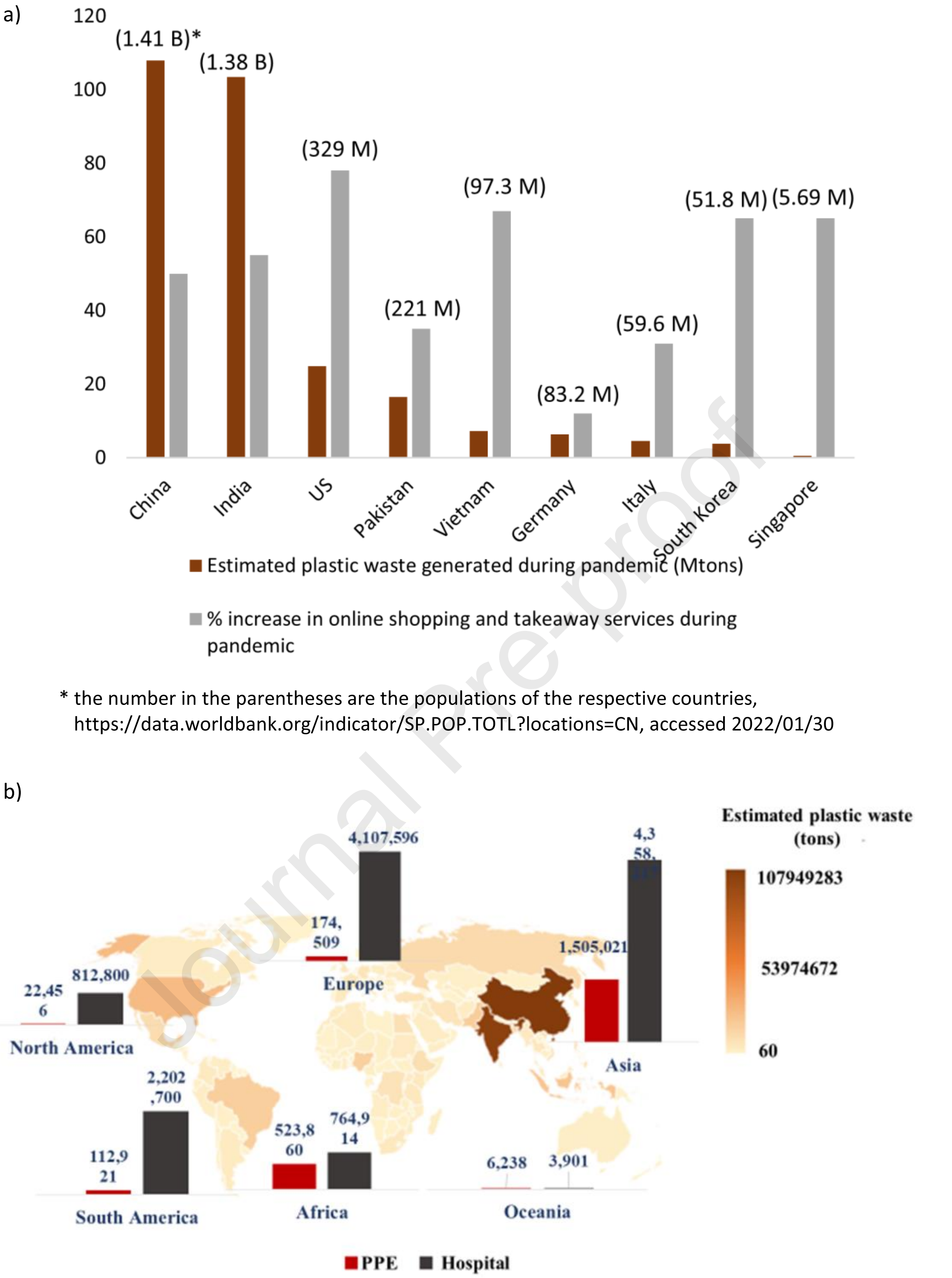

Figure 1. a) Increase in online shopping and takeaway services during the pandemic for selected countries/areas, and the respective amount of plastic waste generated. Data sourced from Parashar and Hait (2021) and Benson et al. (2021); b) Pandemic-related plastic waste generated globally, especially PPE and hospital waste. The figure is created using the data compiled from the work of Benson et al. (2021) and Peng et al. (2021).

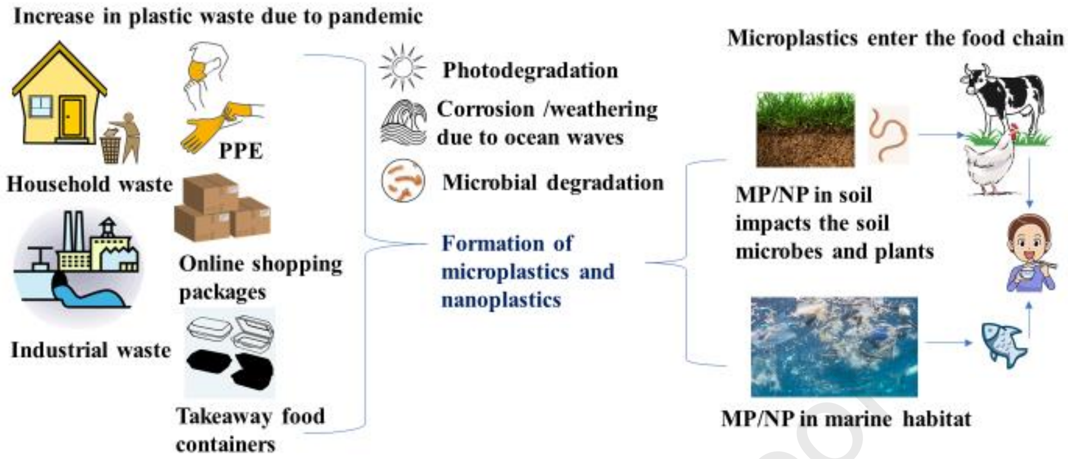

Figure 2. Generation, environmental processes, and ultimate fates of MP/NP during pandemic.

Highlights:

- COVID-19 pandemic-generated plastic is adding to the worldwide plastic pollution.
- Limited awareness of pandemic-generated plastic as a source of microplastic.
- Risk mitigation measures include the use of eco-friendly plastic.
- Include mandatory regulation regarding single-use plastic in waste management plan.
- Microplastic risk to soil biota and human health needs extensive research.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: